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EVALUATION OF THE PERFORMANCE OF ELECTRONIC WHEEL ALIGNMENT EQUIPMENT

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Contents

1. INTRODUCTION

Electronic wheel alignment sensors use transducers to measure small angles, from which the alignment angles of the vehicle wheels are computed. Manufacturers of wheel alignment equipment traditionally will specify the performance of the angle transducers and the computed alignment results. The methods used to specify performance will vary widely from manufacturer to manufacturer.

Evaluation of the performance of electronic wheel alignment equipment by the users of such equipment is often necessary in order to be confident that the equipment is the best choice for their needs. A key factor in this evaluation is that overall alignment system performance is affected not only by transducer accuracy, but by sensor design, wheel adapter design, proper sensor mounting by the operator, and vehicle characteristics. These factors should all be considered in this evaluation.

The purpose of this paper is to explain the methods developed at Hunter Engineering to objectively evaluate performance. It will also define factors that must be considered when system-level performance is being evaluated. System-level performance is what most users are interested in.

2. TRANSDUCER ANGLES VS. COMPUTED ALIGNMENT ANGLES

A front alignment sensor contains four angle transducers;

1. Caster adjust transducer,
2. Camber transducer,
3. Transverse toe transducer,
4. Longitudinal toe transducer.

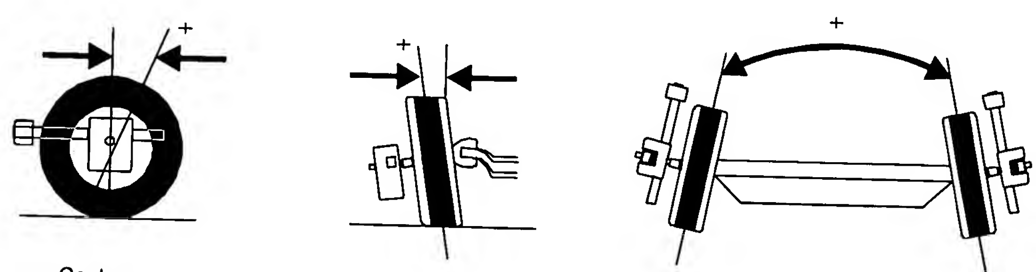


Figure 1: Alignment Angles

These transducers have been designed and calibrated to measure their angle with respect to the vertical (camber and caster adjust) or with respect to a rectangular calibration fixture (transverse and longitudinal toe). The vertical reference used to calibrate camber fortunately is the same reference used in the definition of camber on a vehicle wheel. Therefore, a calibrated and compensated camber transducer angle is identical by definition to the camber computed alignment angle.

The toe angles, however, are more complicated. The computed toe alignment angles are defined with respect to the vehicle thrust line or centerline. This definition requires the use of at least two toe transducer angles from at least two sensors to calculate any computed toe angle. Individual front toe angles, for example, are computed from all six toe transducer angles when using the vehicle thrust angle reference.

There is no transducer that can directly measure the caster of a vehicle wheel. The caster measurement is computed using the camber and longitudinal toe transducer angles at two different steering positions. The caster adjust transducer is only useful to indicate relative change in the caster of wheel during caster adjustment procedures.

Since the computed alignment angles often depend on combinations of transducer angles, the performance specifications of angle transducers cannot be the same as the specifications for computed alignment angles. With the exception of camber, the performance specification of any given transducer should be better than a computed alignment angle that is derived from that transducer. In general, users of wheel alignment equipment are most interested in computed alignment angles, and in particular, the accuracy specifications of the computed alignment angles.

3. DEFINITION OF TERMS

The statistical terms often used to help specify the performance of a measurement are discussed below.

Resolution:

The resolution of a transducer is the smallest angular change which can be detected. The accuracy of a transducer cannot be greater than its resolution

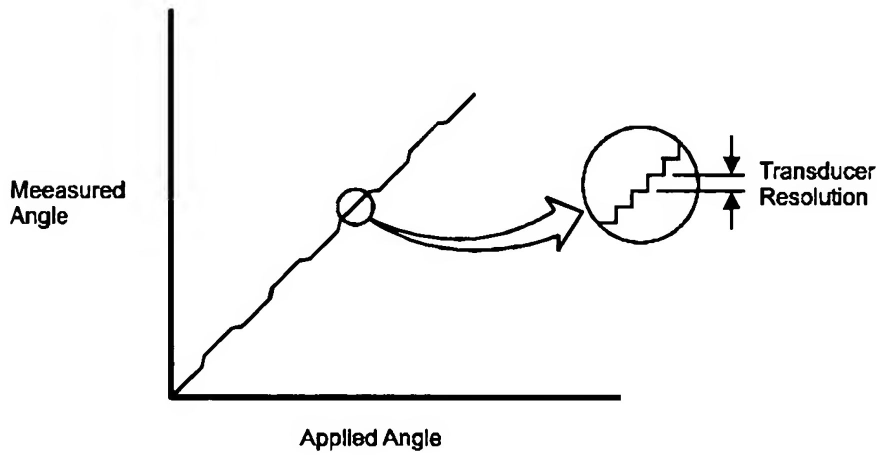


Figure 2: Resolution

Linearity:

The linearity of an angle transducer is the variation of the actual measurements from a straight line characteristic. The accuracy of a transducer also cannot be greater than its linearity. A transducer which measures zero degrees at any applied angle is perfectly linear, but obviously inaccurate.

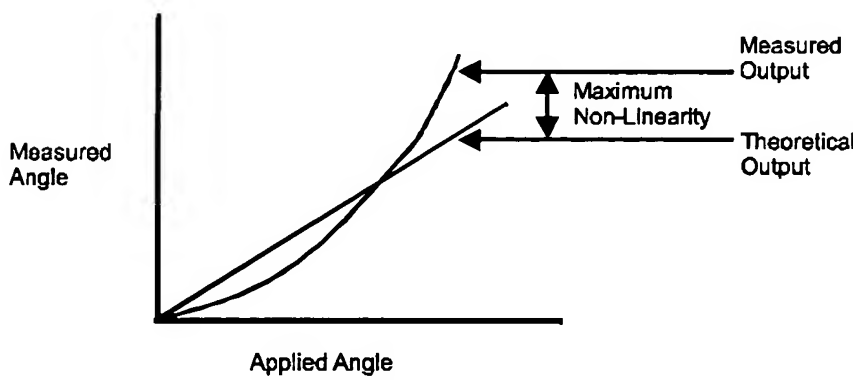


Figure 3: Linearity

Accuracy:

The accuracy of an angle transducer or computed alignment angle is the difference between the average measurement of an angle by the transducer and the actual value or "true average" of the angle. This is normally the performance specification that alignment users are interested in.

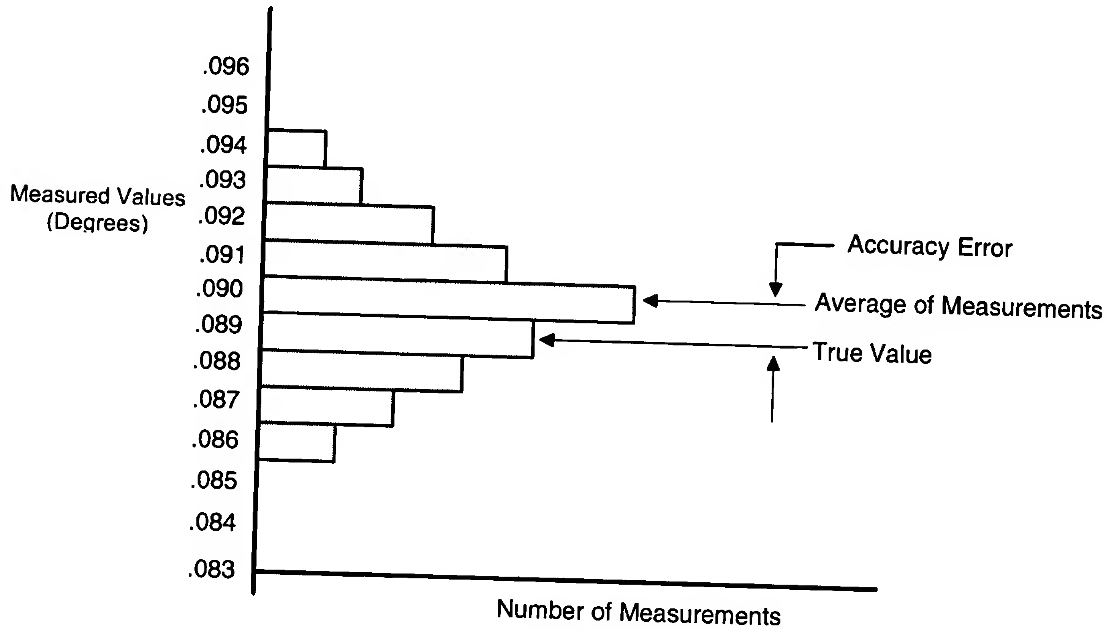


Figure 4: Accuracy

Reproducibility:

The reproducibility of an angle transducer or computed alignment angle is the variation obtained when more than one person, using the same sensors, measures the same angles.

Repeatability (also known as Precision):

The repeatability of an angle transducer or computed alignment angle is the variation obtained when one person, using the same equipment, measures the same angles two or more times. Since accuracy is normally defined in terms of an average of measurements, it is possible, though undesirable, for a transducer angle or computed alignment angle to exhibit high accuracy yet poor reproducibility or repeatability.

Accuracy vs. Precision:

Confusion often exists between the terms accuracy and precision. The terms are often incorrectly used interchangeably. The accuracy of an instrument can normally be improved by re-calibrating to reduce its error, but re-calibration generally does not improve the precision of an instrument. An extremely precise instrument can also be very inaccurate.

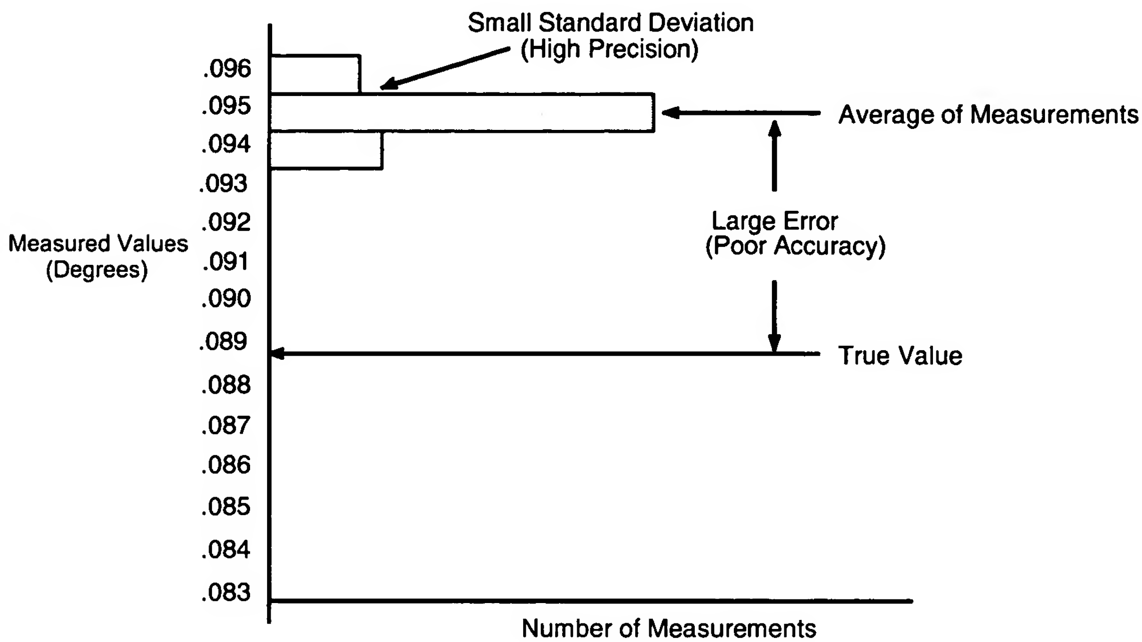


Figure 5: Accuracy vs. Precision

Alignment angle transducers are normally specified in terms of resolution, linearity, accuracy and/or repeatability. Computed alignment angles are normally specified only in terms of accuracy, repeatability and/or reproducibility.

	Transducers	**Computed Alignment Angles**
Resolution	✓	
Linearity	✓	
Accuracy	✓	✓
Repeatability	✓	✓
Reproducibility		✓

Table 1: Applicability of Statistical Terms To Alignment Transducers and Computed Alignment Angles

4. PERFORMANCE ENVELOPE OF SPECIFICATIONS

Any specification, whether for a transducer angle or computed alignment angle, should specify under what conditions it is valid. For example, a transducer may be linear within 1% between -2 and +2 degrees, however outside of this range the linearity might be specified at 2%.

Other conditions besides range should also be considered. Depending on their operating principle, transducer outputs are often dependent on temperature and humidity, therefore the maximum and minimum temperature and humidity where the specification is valid should be specified.

Likewise, modern wheel alignment transducers are designed to measure angles and not be affected by the separation distance between transducers. Therefore, the maximum and minimum wheelbase and track width of the vehicle to be aligned should be specified.

5. CALIBRATION

Precision measurement instruments such as wheel alignment sensors normally require calibration. This procedure combines mechanical adjustments, electrical adjustments and software corrections so that the output of the instrument will accurately reflect the true value.

For wheel alignment angle transducers, calibration is normally a combination of zero calibration and range calibration. Zero calibration requires a known vertical reference for camber and caster adjust, and a known rectangular reference for toe. When the transducer is applied to these references, its output is adjusted until it indicates the known reference angle.

Range calibration requires a change in angle in the geometric plane in which the transducer is sensitive. This change in applied angle is used to adjust the gain or range constant of the angle transducer, such that the change in angle indicated by the transducer is equal to the applied change.

It is generally considered a requirement for alignment sensors to be re-calibrated periodically without the need to return them to the manufacturer. Some manufacturers allow zero re-calibration only in the field and some allow both zero and range re-calibration. Since the accuracy of the transducers and the computed alignment angles is greatly affected by calibration, any accuracy specifications provided should be valid after both factory calibrations and field re-calibrations.

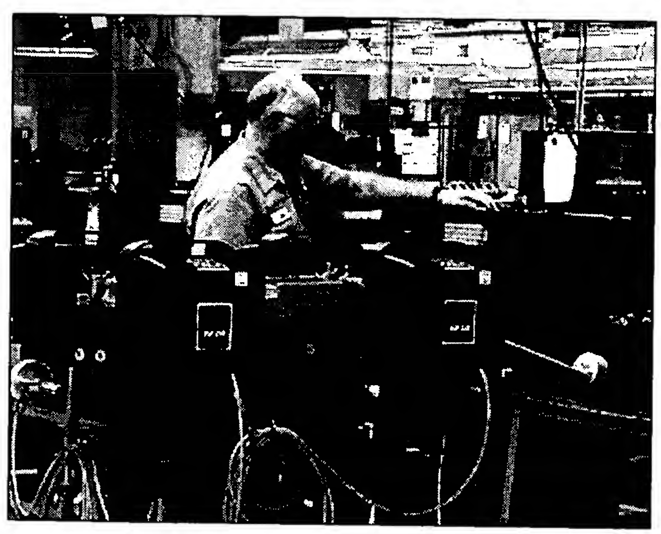


Figure 6: Calibration Stand

6. TEST EQUIPMENT AND TEST FIXTURES

Hunter Engineering has designed or purchased test fixtures and test equipment, which are used in research and development to determine different angle transducer and computed alignment angle performance specifications. Production test fixtures generally use the same principles as described below, however may not in all cases be as exhaustive.

6a. Test Fixtures

Theodolite

It is generally a requirement of any alignment test fixture used to test zero calibration to be rigid and any fixture used to test range calibration to have high resolution and incremental accuracy. Hunter Engineering uses a theodolite measuring instrument (model T2) manufactured by Wild Heerbrugg Ltd., Heerbrugg Switzerland to check the performance of these test fixtures. The theodolite is equipped with a telescope which provides 30x magnification. Both horizontal and vertical angles can be measured to one second of arc accuracy. For optical tooling measurements, the theodolite can be converted to an autocollimation instrument by exchanging the standard telescopic eyepiece for an autocollimation eyepiece.

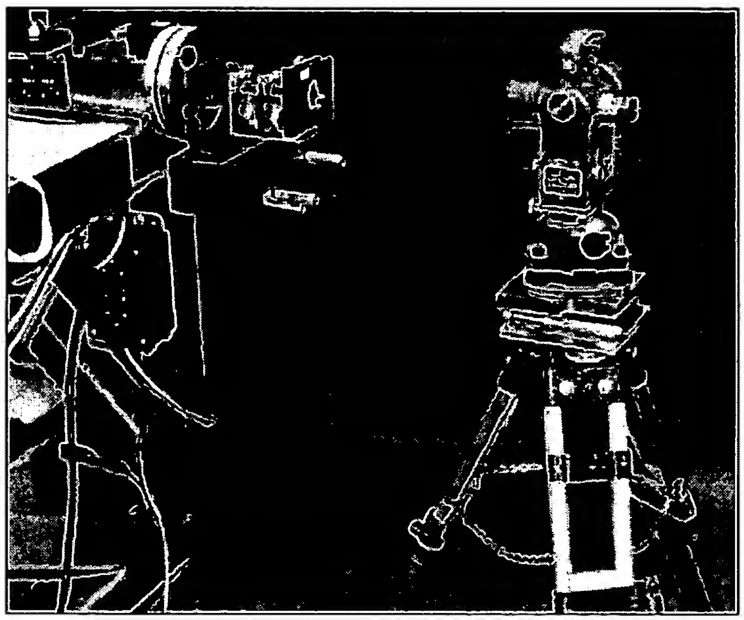


Figure 7: Theodolite

Environmental Chamber

A 6 foot square by 8 foot high (1.8 m x 1.8 m x 2.4 m) environmental chamber is used to subject the equipment to changes in temperature and humidity. The temperature can be controlled from -30° F to 185° F (0°C to 85° C). The humidity can be controlled from 20% to 95%. The chamber is manufactured by Envirotronics and the controller by J.C. Systems.

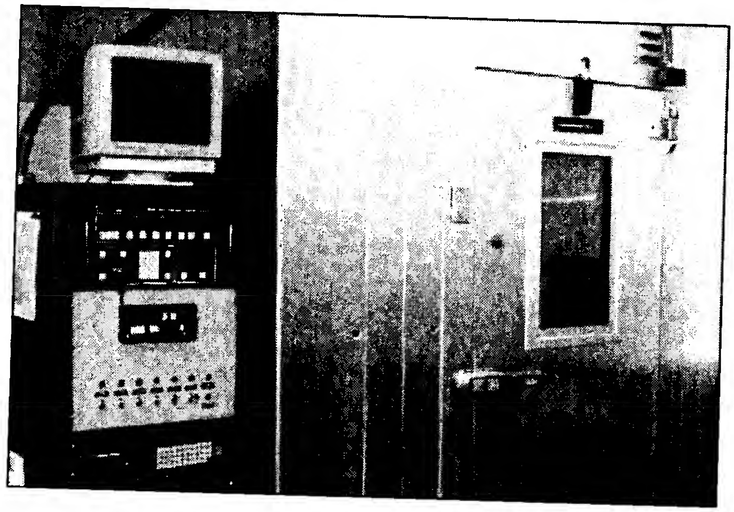


Figure 8: Environmental Chamber

6b. Transducer Angle Fixtures

Camber Transducer Performance Test Fixture

Performance testing of camber and caster transducers is accomplished using an orthogonal pair of goniometric cradles (part number BG 80 and BG 120) manufactured by Klinger Scientific. Each cradle contains a stepper motor. Both stepper motors can be controlled simultaneously with a two channel programmable stepping motor controller (part number CC-1) also manufactured by Klinger Scientific. Hunter Engineering has designed a computer based data acquisition system which can monitor 16 individual camber/caster transducers simultaneously and control the programmable stepper motor controller. Each cradle has a resolution of 0.001 degrees. The system is capable of operating inside the environmental chamber.

Typical testing would include zero and range calibration, full characterization of input angle vs. measured angle, return to zero testing, and sensitivity to movement in the orthogonal plane (referred to as crosstalk). Specific testing would also be performed throughout the temperature and humidity range of the transducer.

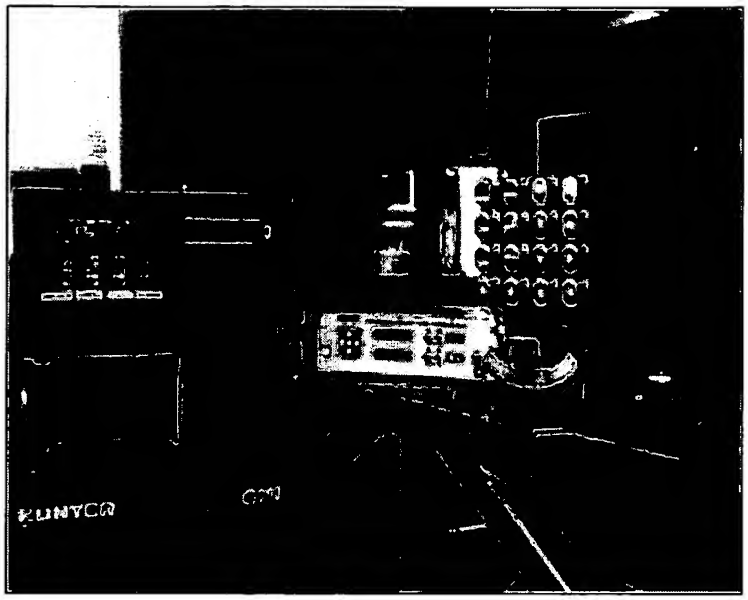


Figure 9: Camber Transducer Performance Test Fixture

Toe Transducer Performance Test Fixture

Performance testing of toe transducers is accomplished using a rotational micropositioning stage (part number RT 120) manufactured by Klinger Scientific in conjunction with the same programmable stepper motor controller described above. The rotational stage has a resolution of 0.001 degrees. The system is capable of operating inside the environmental chamber.

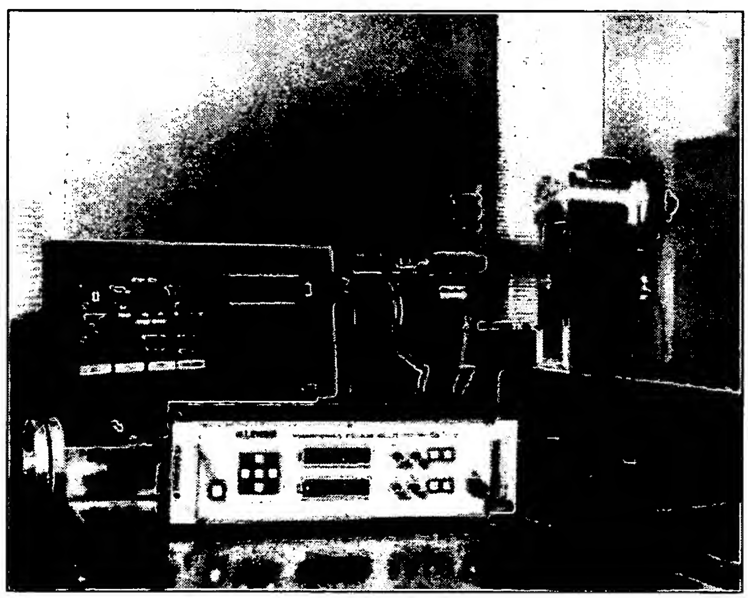


Figure 10: Toe Transducer Performance Test Fixture

Typical testing would include zero and range calibration, full characterization of input angle vs. measured angle and return to zero testing. Specific testing would also be performed throughout the temperature and humidity range of the transducer.

Some sample transducer performance plots are shown below.

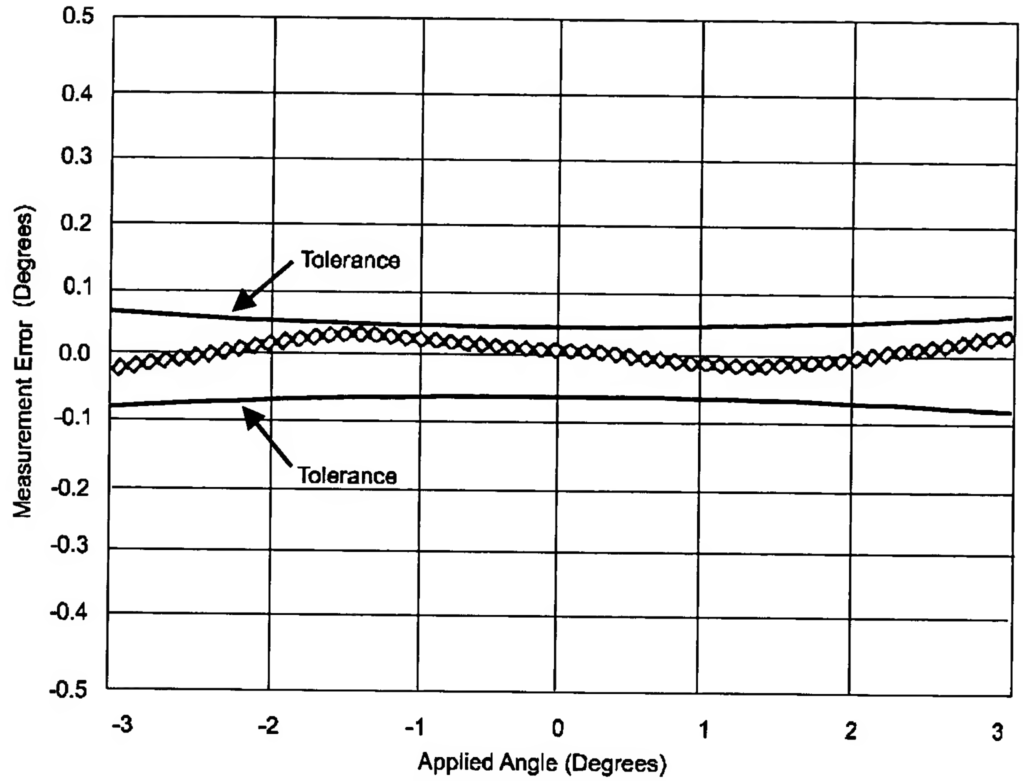


Figure 11: Transducer Accuracy - Optical Toe Rear

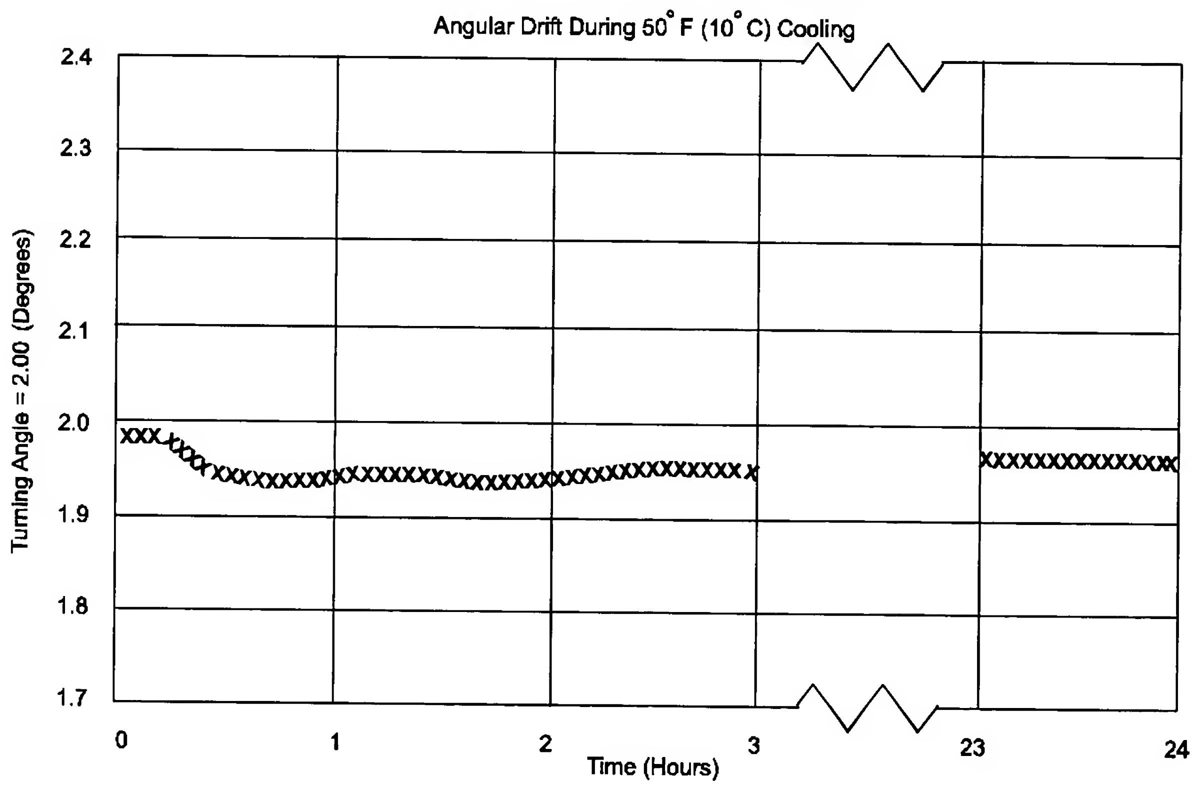


Figure 12: Camber Transducer Temperature Plot

Toe Transducer Variable Wheelbase Fixture

Toe transducers are designed to measure angles and not be affected by the separation distance between cooperative pairs of transducers. A rail was designed at Hunter Engineering to characterize the sensitivity of a toe transducer to changes in wheelbase or track width. The rail incorporates two transducer testing stations - one stationary and one capable of translating up to 6 feet (1.8 m). The translating station has a transducer mount which can be adjusted in two orthogonal linear directions and two rotational axes. The stationary transducer mount is adjustable in one axis and normally controlled by the RT 120 rotational micropositioning stage described on page 8.

With this tool, the near and far field beam patterns of the individual transducers can be accurately mapped and the electronic gain compensation for variable transducer distances can be checked. The angles are adjustable with .001 degree resolution and the rail travel does not deviate from a straight line by more than .001 inches (0.0254 mm) at any point in its motion.

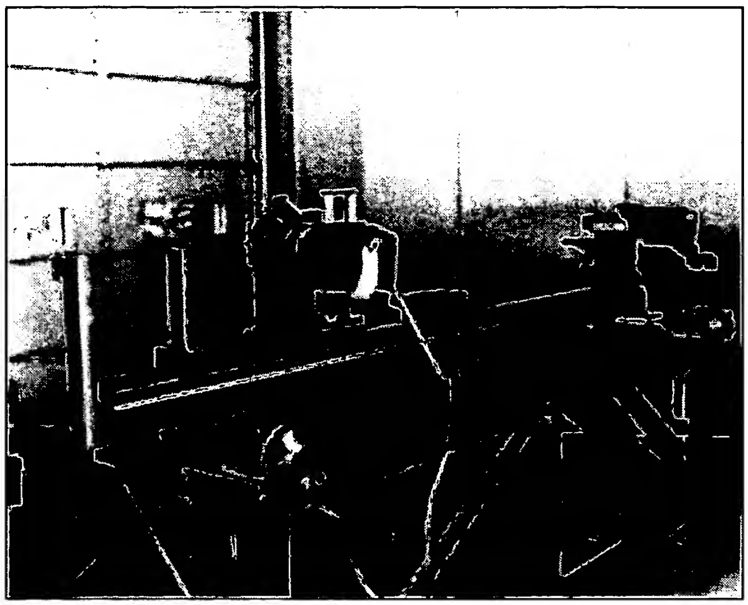


Figure 13: Toe Transducer Variable Wheelbase Fixture

6c. Alignment System Test Fixtures

Zero Angle Fixture

The zero angle fixture consists of a welded frame of 3 inch (76.2 mm) rectangular mechanical tubing which is filled with sand and bolted to the ground. The fixture contains provisions for leveling each leg and for compensating any sensor for angular runout.

The purpose of the zero angle fixture is to provide a very accurate, very stable, large wheelbase, zero angle reference fixture. It has a nominal 54 inch (1371.6 mm) track width and a 100 inch (2540 mm) wheel base. The spindles are boresighted by theodolite so that all transducer angles are known and between +.001 and -.002 degrees.

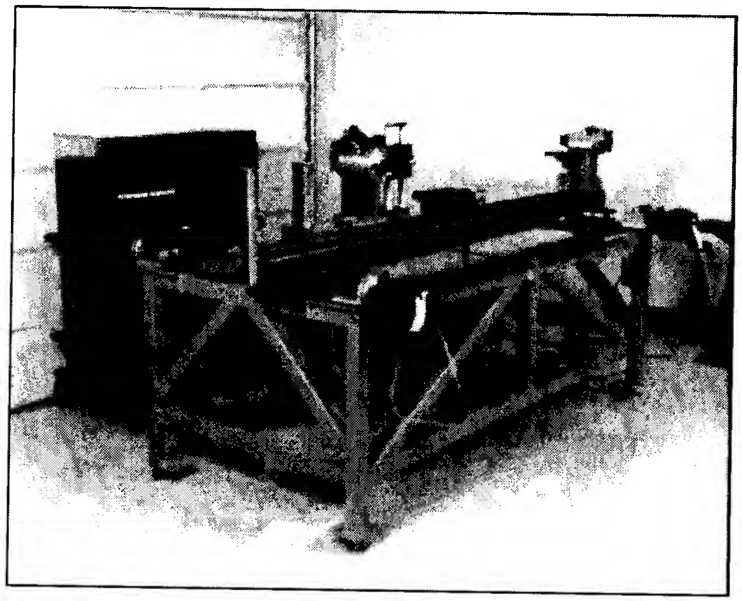


Figure 14: Zero Angle Fixture

This fixture can be used to check the zero accuracy and repeatability of any individual transducer, any computed alignment angle, or a complete set of 4 sensors.

Typical testing would include calibrating a set of sensors, mounting them one or more times on the zero angle fixture, and monitoring the deviation of any of the transducer angles or computed alignment angles from zero.

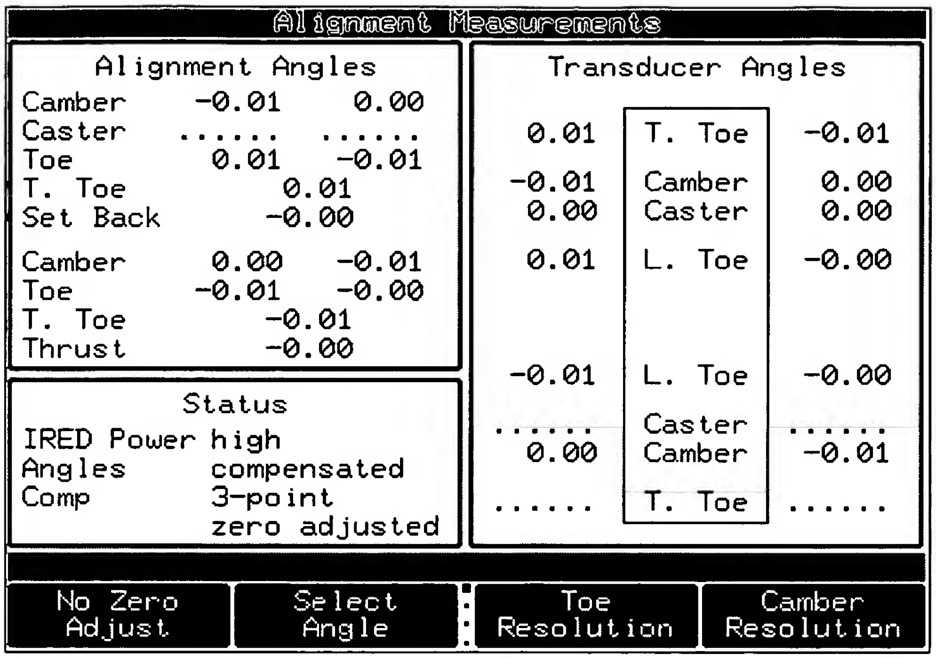
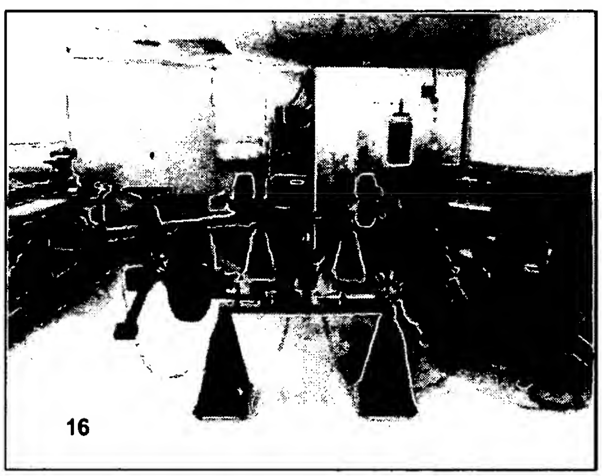
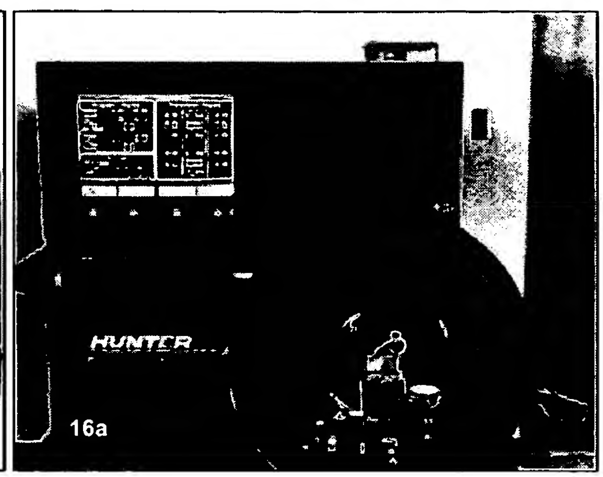


Figure 15: Sample Measurements (Degrees) of Zero Angle Fixture

Incremental Angle Fixture

The incremental angle fixture consists of a frame which supports four standard 15 inch diameter vehicle wheels. The wheelbase and each track width is adjustable. In addition, each individual wheel is adjustable for setback and toe. Toe angles changes are measured to greater than .01 degree resolution using a dial indicator at each wheel.





Figures 16 and 16a: Incremental Angle Fixture

It is important to note that this fixture is not rigid, thus it can not be used to test the absolute accuracy of any transducer or computed alignment angle. This fixture is most useful in the evaluation of the incremental accuracy of computed alignment angles.

Typical testing would include mounting a set of calibrated sensors to the incremental angle fixture using wheel adapters, electronically or mechanically zero adjusting the computed alignment values, adjusting the toe or setback of an individual wheel and monitoring all computed alignment values to insure that they accurately reflect the incremental change.

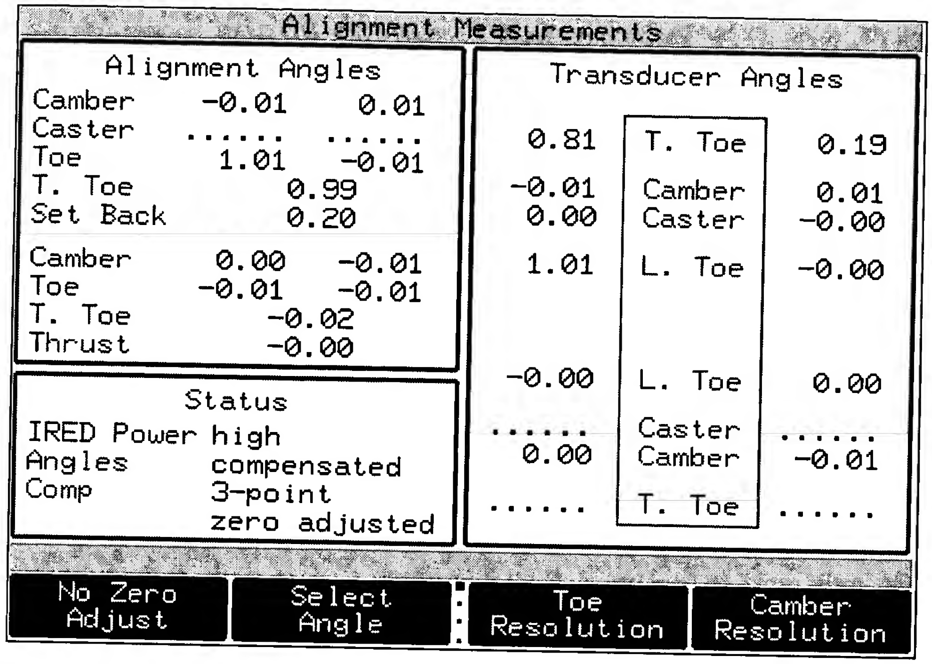


Figure 17: Sample Measurements (Degrees) of Incremental Angle Fixture

7. USING A VEHICLE AS A TEST FIXTURE

All vehicle suspensions have compliance. Suspension compliance exists in part by design and in part because of wear of suspension components. This compliance means that the geometric relationship between the wheels and the body of the vehicle can change without making any type of alignment adjustments.

Likewise, all suspensions have friction. This suspension friction, in addition to any friction between the tires and the alignment rack, along with the suspension compliance means that all suspensions will exhibit hysteresis. In other words, when the suspension is disturbed, there is no reason to believe that the wheels will return to their initial position.

An actual alignment angle of a vehicle must be thought of as a mean value with a distribution of values on either side of this mean. Confusion often exists when a vehicle is repeatedly measured and each measurement does not repeat. The procedure of compensating for wheel runout alone can disturb the suspension enough to change the current alignment measurements significantly. The wheel alignment procedure is only a snapshot of the vehicle alignment characteristic at that time.

Since the actual alignment of the vehicle is always changing, it is very difficult to evaluate alignment equipment accuracy specifications on a vehicle. One possible way is to measure the vehicle alignment with some additional, extremely accurate method at the same time (thus the same vehicle position) as the alignment sensors. This additional method must not interfere with the normal alignment process (i.e. not require the removal of the alignment sensors). Combinations of theodolites, inclinometers, and scribe bars have been used successfully to confirm the measurements of wheel alignment equipment while on a vehicle.

Gage repeatability and reproducibility studies can also be applied. These methods can be used successfully to separate the contribution of variables including the alignment equipment from the repeatability of the measurements. These methods cannot be used to determine the accuracy of the alignment equipment.

Repeatability testing of alignment equipment using a vehicle instead of a rigid test fixture is often attempted. In order to eliminate the variance caused by vehicle compliance, the vehicle should be made as rigid as possible. This can best be done be jacking up each axle underneath the control arms or trailing arms, and then leaving the vehicle in this condition. The alignment equipment can now be repeatedly mounted and compensated and successive measurements can be compared.

8. WHEEL ADAPTERS

Wheel adapters are the mechanical devices used to attach an alignment sensor to a vehicle wheel. The design and performance of the wheel adapter is critical for alignment system accuracy.

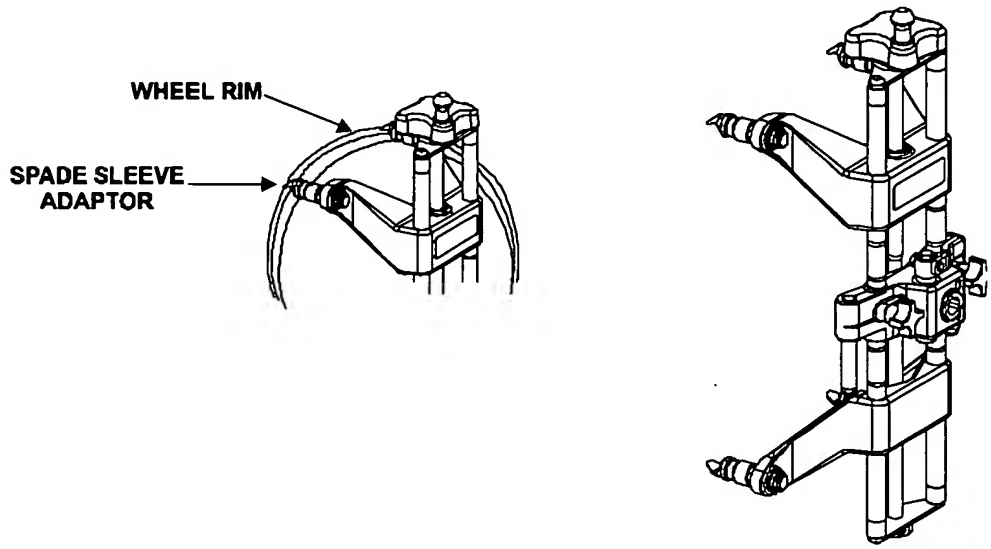


Figure 18: Wheel Adapter with Spade Sleeve Adapters

A wheel adapter must be able to rigidly mount to any possible wheel type. Manufacturing advances in wheel and tire design has made this increasingly difficult, but it is essential for accurate alignment. Even the smallest amount of looseness, slippage, or "rocking" in the mounting will produce alignment errors.

The wheel adapter design must also provide for rigidly attaching the sensor to the wheel adapter. Typically a sensor has a protruding shaft which is inserted into the wheel adapter. The sensor must be easily removable from the wheel adapter, so the tolerance between these parts cannot be too tight. However, once attached, the shaft must not be able to wobble or slip, which would introduce alignment errors.

The errors introduced by improper wheel adapter design or mounting cannot be underestimated. A hard to use or poorly designed wheel adapter will result in improper mounting and increased errors, regardless of sensor transducer accuracy.

9. RUNOUT

Runout is defined as the amount of angular deviation in the axis of rotation of the sensor shaft relative to the axis of rotation of the wheel as the wheel is rotated.

There are many mechanical factors that contribute to the total runout of the sensor / wheel. Runout is typically compensated for in electronic wheel aligners by a procedure in which each wheel is rotated once after the sensor has been mounted. The angular changes during this rotation are measured by the wheel alignment sensors and stored. These compensation procedures "compensate" for the runout of the wheel rim, the sensor shaft, the wheel adapter, and the mounting of the wheel adapter to the wheel.

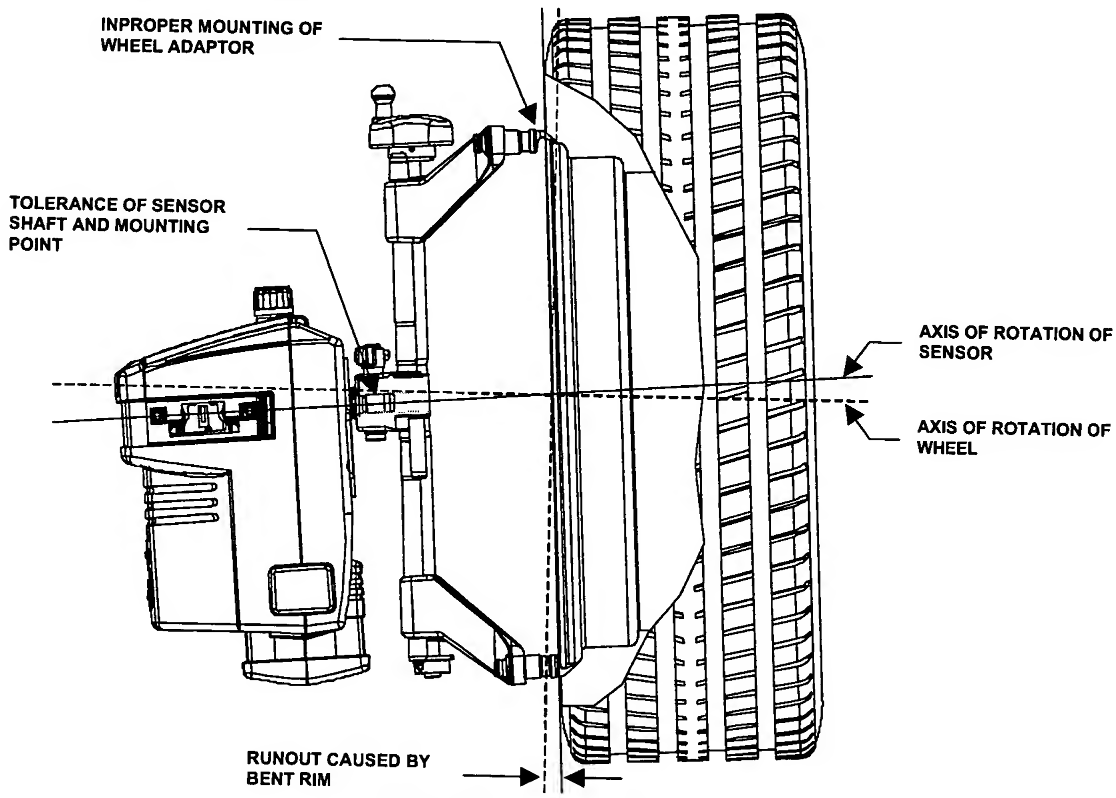


Figure 19: Typical Runout Sources

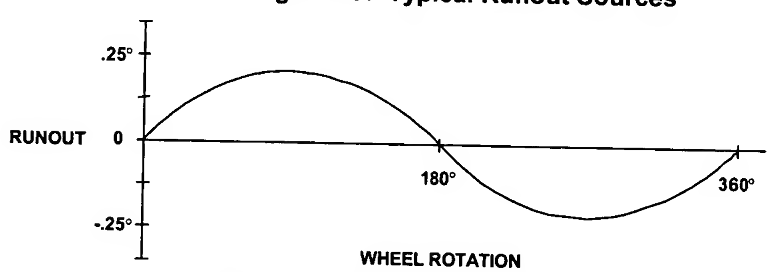


Figure 20: Change In Runout As Wheel Is Rotated

Compensation procedures make the assumption that as the wheel rotates about its axis (spindle), the axis of the wheel does not move. If the axis moves due to suspension compliance, loose wheel adapters, or external forces from the operator during the compensation procedure, the stored runout measurement will be a combination of the true runout and the angular changes from these error sources. Care should be taken when evaluating wheel alignment equipment to insure that the axis of rotation of the wheel does not move, that the sensor is mounted rigidly, and that the operator does not disturb the fixture, vehicle or sensor other than to rotate the wheel.

10. SYSTEM-LEVEL PERFORMANCE CRITERIA

When comparing Manufacturers' accuracy figures for alignment angles, such as computed front toe, it is difficult to compare "apples-to-apples" due to the many system-level factors involved. For instance:

- Is the test fixture a vehicle?
- Are wheel adapters used?
- How much runout, if any, is in the wheels or test fixture?
- What test equipment and procedures were used to determine/verify accuracy?

Errors during testing can also cause accuracy and repeatability problems. Common sources of errors that may cause accuracy specifications to appear incorrect are:

- Improper mounting of wheel adapter to wheel.
- Improper mounting of sensor to wheel adapter.
- Using a vehicle as a test fixture.
- Calibration errors caused by improper technique or equipment when calibrating.
- Disturbing the suspension during compensation.

11. CONCLUSIONS

Manufacturers of vehicle wheel alignment equipment specify many statistical characteristics of wheel alignment angle transducers and computed alignment angles. In general, the users of such equipment are primarily interested in the accuracy specifications of the computed alignment angles.

Evaluation of the accuracy of electronic wheel alignment equipment cannot be done by repeatedly measuring a vehicle with one set of alignment instruments. The change in the vehicle alignment due to suspension compliance and friction are not insignificant and can often cause changes in alignment angles in excess of the absolute accuracy specifications of the wheel alignment equipment.

Evaluation of all performance specifications of alignment angle transducers and computed alignment angles is performed at Hunter Engineering using test equipment and fixtures designed to test specific characteristics of angle transducers and computed alignment angles.

12. BIBLIOGRAPHY

1. Datamyte Handbook: A Practical Guide to Computerized Data Collection For Statistical Process Control. DataMyte Corporation, Second Edition, January 1986.
2. Statistical Quality Control. E. L. Grant, McGraw-Hill, New York, 1946.
3. Measurement Systems Analysis Reference Manual. A.I.A.G., 1990.

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